

NASA-TM-87147

NASA Technical Memorandum 87147

NASA-TM-87147 19860014383

# Liquid-Vapor Interface Locations in a Spheroidal Container Under Low Gravity

Michael J. Carney  
*Lewis Research Center*  
*Cleveland, Ohio*

LIBRARY COPY

MAY 23 1986

LANGLEY RESEARCH CENTER  
LIBRARY, NASA  
HAMPTON, VIRGINIA

April 1986



NF01475

**NASA**

# LIQUID-VAPOR INTERFACE LOCATIONS IN A SPHEROIDAL CONTAINER

## UNDER LOW GRAVITY

Michael J. Carney  
National Aeronautics and Space Administration  
Lewis Research Center  
Cleveland, Ohio 44135

### SUMMARY

As a part of the general study of liquid behavior in low-gravity environments, an experimental investigation was conducted to determine if there are equilibrium liquid-vapor interface configurations that can exist at more than one location in oblate spheroidal containers under reduced gravity conditions. Static contact angles of the test liquids on the spheroid surface were restricted to near  $0^\circ$ . The experiments were conducted in a low-gravity environment (on the order of  $1 \times 10^{-5}$  g). An oblate spheroidal tank was tested with an eccentricity of 0.68 and a semimajor axis of 2.0 cm. Both quantitative and qualitative data were obtained on the liquid-vapor interface configuration and position inside the container. The results of these data, and their impact on previous work in this area, are discussed. Of particular interest are those equilibrium interface configurations that can exist at multiple locations in the container.

### INTRODUCTION

With the evolution of Orbit Transfer Vehicles (OTVs) and other high performance liquid propellant upper stage rockets, new problems in the area of low-gravity propellant management have arisen. Several of these problems are concerned with the dynamics of liquid propellants during various perturbation maneuvers a space vehicle may encounter prior to, or during its deployment. Many times these activities take place in earth orbit or other low-gravity environments. An example of a low gravity maneuver which has an effect on propellant management concerns the Centaur upper stage. The Centaur is a liquid hydrogen/liquid oxygen rocket that is scheduled to be used with the Space Shuttle in 1987. The shuttle will bring Centaur to low earth orbit where the upper stage will be deployed. Separation of Centaur from the Space Shuttle, however, may create motion of the liquid propellants in the fuel or oxidizer tank of the upper stage. This resulting propellant motion causes forces which are imparted to the tank and consequently to the vehicle during deployment (ref. 1). These forces could significantly affect the dynamics of the upper stage as it separates from the Shuttle. A thorough understanding of this low-gravity liquid behavior is critical for successful mission performance.

In order to identify potential problems dealing with the dynamics of low-gravity liquid-vapor systems, it is essential that a complete description of the initial liquid-vapor interface - prior to any disturbance - be known. This equilibrium liquid-vapor interface has been discussed in several previous reports (refs. 2 and 3). These early studies have shown that the liquid-vapor interface shape is dependent on several system conditions, such as Bond number (ratio of acceleration to capillary forces), liquid fill level, contact angle

F-2936

1086-23854#

and tank geometry. Since tank geometry is of prime importance to the spacecraft designer, earlier investigations which studied low-gravity fluid mechanics considered a variety of container shapes such as cylinders, spheroids, toroids and others (refs. 4 to 6). Of particular interest, because of its direct application to the Centaur and future space vehicles, is the oblate spheroid (generated by the rotation of an ellipse about its minor axis).

The subject of low gravity equilibrium liquid-vapor interface configurations in oblate spheroidal containers has been addressed in terms of a theoretical analysis by Concus, Crane, and Satterlee (ref. 7). In reference 8, an experimental investigation of low-gravity interface shapes in spheroidal containers was reported which helped verify the theoretical work. These reports laid a foundation for later research which focused on reduced gravity sloshing characteristics in oblate spheroidal tanks (ref. 9). Although this early work aided in the understanding of the general behavior of low-gravity liquid-vapor systems in spheroidal containers, it considered only interface configurations symmetric about the tank minor axis. This results in a limited understanding of these liquid-vapor systems, since locations of equilibrium interface configurations other than those symmetric about the tank minor axis may be possible. Because a complete knowledge of the equilibrium interface is an integral part of understanding zero-gravity liquid dynamics, a study to determine locations where liquid-vapor configurations may or may not exist in an oblate spheroid would have both practical and scientific value.

This report presents the results of an experimental investigation where test conditions were varied in order to examine the possibility that quiescent, liquid-vapor configurations may exist at more than one location in an oblate spheroid under zero-gravity. The liquids used in this study had static contact angles very near  $0^\circ$  on the spheroid surface, and the experiments were conducted in a low-gravity environment ( $10^{-5}$  g). An oblate spheroid tank with an eccentricity of 0.68 was tested. This was the only tank geometry used, because of its direct application to the Centaur space vehicle. Data on the low-gravity static equilibrium liquid-vapor interface were obtained through both quantitative and qualitative methods. The results are compared with previous work where only interface configurations symmetric about the tank minor axis were considered (refs. 7 and 8). Of particular interest are those equilibrium interface configurations that show a capability of existing at various positions in the container.

#### SYMBOLS

- a system acceleration,  $\text{cm/sec}^2$
- $Bo$  Bond number,  $Bo = ax^2/\beta$
- e tank eccentricity,  $e = \sqrt{1-(y^2/x^2)}$
- g acceleration due to gravity,  $981 \text{ cm/sec}^2$
- x tank semimajor axis, cm
- y tank semiminor axis, cm

- $\beta$  specific surface tension, ratio of surface tension to density,  
 $\text{cm}^3/\text{sec}^2$
- $\theta$  static contact angle of test liquid on container surfaces, degrees
- $V_L$  volume test liquid occupies in tank,  $\text{cm}^3$
- $V_t$  tank volume,  $\text{cm}^3$

## APPARATUS AND PROCEDURE

### Test Facility and Experiment Vehicle

The reduced gravity data presented in this report were obtained in the NASA Lewis Zero Gravity Facility. A schematic diagram of this facility is shown in figure 1. The facility consists of a concrete-lined 8.5 m diameter shaft that extends 155 m below ground level. Contained within the concrete shaft is a steel vacuum chamber, 6.1 m in diameter and 142 m long. The pressure in this vacuum chamber is reduced to  $13.3 \text{ N/m}^2$  ( $1.3 \times 10^{-4} \text{ atm}$ ) by utilizing the NASA Lewis wind tunnel exhaust system in series with vacuum pumps located in the facility. Approximately 5 sec of free-fall time is available by allowing a vehicle to drop the length of the vacuum chamber.

During this 5 sec, the vehicle falls with no guides or electrical lines connected to it. Since the experiment is falling freely in an evacuated environment, the only effective force (aside from gravity) acting on the test package is that due to residual air drag. This drag results in an equivalent gravitational acceleration acting on the experiment which is estimated to be no greater than  $10^{-5} \text{ g}$ . Following the free-fall period, the vehicle and experiment are recovered at the bottom of the chamber in a cart filled with small pellets of expanded polystyrene. The average deceleration of the vehicle is 32 g's.

In addition to the drop chamber, the Zero Gravity Facility has as its major elements, a shop area, a control room, and a clean room. Assembly and servicing of the experiment vehicle are accomplished in the shop area. The drop tests are controlled and monitored from the control room which contains the exhaust control system and the experiment vehicle pre-drop checkout system.

The experiment vehicle used to obtain the reduced gravity data is shown in figure 2(a). The major part of the vehicle consists of a cylindrical section where the experiment assembly, power supply and control systems are housed. The experimental assembly consists of a test tray shown in figure 2(b). On this tray is mounted the hardware for a particular experiment, which for this test program included the support cradle for the oblate spheroid test container, camera, digital clock, and lighting systems. The test container was mounted in a cradle that was fixed to the test tray. All data were collected during the drop by a high-speed camera, which photographed the liquid-vapor interface at a rate of 400 frames/sec. Time measurements were made by placing a digital clock in the field of view of the camera, and from timing marks placed on the edge of the data film by a pulse generator. Both time bases were accurate to 0.01 sec. Illumination was by diffuse backlight-

ing. The source supplying the electrical power to the experimental apparatus was located below the test tray and consisted of 28-V battery packs (2-V batteries wired in series). From this section, direct current was relayed and regulated to the experiment. During the test drop the entire cylindrical section of the test vehicle was covered with aluminum side panels to minimize aerodynamic drag and protect the experiment assembly during the deceleration of the vehicle at the bottom of the chamber.

### Test Container and Liquids

The test container was an oblate spheroid formed from clear acrylic plastic, with semimajor and semiminor axes of 2.00 and 1.47 cm, respectively (fig. 3). The eccentricity of the tank is 0.68 - where eccentricity is defined as  $e = \sqrt{1 - (y^2/x^2)}$  (here,  $x$  is the semimajor axis and  $y$  is the semiminor axis). The test container has an internal volume of 24.63 cm<sup>3</sup>.

The spheroidal container has two distinct areas where the wall curvature has a maximum and minimum value. The container boundary at the minor axis has the largest radius of curvature, while at the major axis this radius is the smallest. For convenience, the area of the tank where the radius of curvature is the largest will be referred to as the central area of the oblate spheroid. Also, the points where the container boundary and semimajor axis intersect will be defined as the vertices of the spheroid (fig. 3).

Ethanol and FC-43 were the liquids used in the experiments. Both liquids exhibited 0° static contact angles on the spheroid walls. Other properties of these liquids, such as surface tension, density, and viscosity are presented in table I. Liquid properties were obtained from standard references and published NASA data. Reasons for using fluids with these properties will be presented later, in the Results and Discussion section of this report. To improve photographic quality, a small quantity of blue dye was added to the liquid. Previous tests have determined that the addition of the dye has no measurable effect on the fluid properties.

### Test Set-up and Procedure

Before each series of tests, the experimental container was cleaned ultrasonically so that contamination of the spheroid surface was avoided. Immediately prior to each test, the spheroidal container was rinsed with a solution of distilled water, dried in a warm-air dryer and then rinsed with the test liquid. After the final rinsing, the container was filled to the required volume at normal atmospheric conditions with a syringe having graduations which provided volume resolution up to 0.02 cm<sup>3</sup>. Once the container was filled to the proper level, it was hermetically sealed, which not only prevented contamination but maintained the internal pressure of the container at one atmosphere while in the vacuum in the test chamber.

The entire test vehicle was then balanced about its vertical axis to ensure an accurate drop trajectory. During this balancing procedure, the cradle on which the test container was mounted was leveled with a precision level. This was done so that vertical and horizontal scribe marks on the yolk of the cradle aligned parallel with, and perpendicular to the drop axis of the vehicle. Once the cradle was leveled, the spheroidal tank was mounted to it

as shown in figure 4. Before the container was firmly fastened to the mount, the scribe marks on the cradle were used as a reference with scribe marks on the tank perimeter in order to assure that the spheroid was oriented in the desired test position. The scribe marks on the tank perimeter denoted the semimajor and semiminor axes of the oblate spheroid. In this investigation the semimajor axis was aligned parallel with or rotated  $30^\circ$  clockwise from the drop axis (fig. 5).

After the container was mounted, the experiment vehicle was suspended at the top of the vacuum chamber by a support shaft (connected to the cylindrical section of the vehicle) on a hinged plate assembly. Once chamber pumpdown was completed, the vehicle was released by pneumatically shearing a bolt that held the hinged plate in the closed position. No measurable disturbances were imparted to the test vehicle by this release procedure. The total free-fall test time obtained was 5.16 sec. Following the drop, the vacuum chamber was vented to the atmosphere and the experiment was returned to ground level.

### Data Analysis

The data obtained in this investigation were collected during the free-fall period by a high speed motion picture camera. This camera was mounted on the test tray so that the optical axis of the camera lens was aligned to within 3 mm of the center of the spheroidal tank. Information on the zero-gravity liquid-vapor interface configuration was taken from the film by use of a film analyzer. From the analyzer, the observed interface shape could be directly plotted. In the test films, the general outline of the interface was defined by a dark band as shown in figure 6. Specifically, the points used for plotting the interface shape followed the outer perimeter of this dark band. Because symmetry of the liquid-vapor interface about the spheroid centerline existed prior to the drop (fig. 7), the interface remained symmetric about the spheroid centerline throughout the drop period. This was true as long as no forces were allowed to act on the test container which may have caused the interface configuration to move in a plane that was not perpendicular to the field of view of the camera. As a result of this symmetry, the outer perimeter of the interface seen in the data films (fig. 6) corresponded to the part of the interface located in the plane defined by the spheroid centerline and the tank minor axis.

This observed interface, however, was distorted due to refraction effects. As a result, it was necessary to correct these data in order to obtain the true liquid-vapor interface shape and position. To do this, a refraction correction procedure - identical with that used in reference 8 was employed, and is illustrated in figure 8. A calibration film was made from the same experimental apparatus and set-up used for the drop tests, only with an etched grid positioned through the test container along the spheroid centerline in a plane containing the tank minor axis. The large degree of distortion due to refraction is shown in a picture taken from the calibration film (fig. 8). By using the calibration film as a reference of where known coordinate points (lying in the plane of the container centerline and tank minor axis) were observed, it was possible to trace corresponding liquid-vapor interface points to their true position. Thus, the actual interface position and configuration were determined. This direct method of correcting for the optical distortion was employed rather than using refraction calculation techniques because of random irregularities in the container wall thickness. As noted in reference 8, it is

not possible to measure the entire curvature of the liquid-vapor interface because refraction losses are extremely high near the tank wall. As a result of these losses, measurement of the liquid edge position where it intersected the wall was generally impossible.

## RESULTS AND DISCUSSION

The dimensionless parameter that characterizes a low-gravity condition for a liquid-vapor interface is the Bond number. The Bond number is the ratio of acceleration to capillary forces acting in a system. In this program the Bond number was defined as

$$Bo = \frac{a x^2}{\beta}$$

where  $x$  is a characteristic dimension (in this case, the container semimajor axis),  $a$  is the equivalent gravitational acceleration, and  $\beta$  is the specific surface tension (surface tension/density) of the liquid. Therefore, acceleration, fluid properties and system size are all necessary to characterize a low gravity liquid-vapor system.

In this study, the only force (aside from gravity) acting on the test vehicle during a drop was that caused by residual-air drag. As discussed previously, this drag results in an equivalent gravitational acceleration acting on the vehicle of approximately  $10^{-5}$  g. For these acceleration values, the Bond number for the experimental system was on the order of  $10^{-3}$ . Bond numbers this low indicate that any fluid behavior will be a result of the action of capillary forces.

Fluid systems at very low Bond numbers have been extensively studied in previous theoretical and experimental work as subsequently described. Much of this work involved hydrostatic analyses, where the minimum energy principle was used to predict the liquid-vapor interface shape (refs. 3, 6, and 7). Key conclusions drawn from these hydrostatic analyses are: (1) the contact angle of a specific liquid-solid combination is constant regardless of changes in the effective gravitational level, and (2) if a stable liquid-vapor interface exists in zero-g, its shape has a constant radius of curvature. Consequently, for a liquid-solid combination whose contact angle is not  $90^\circ$ , liquid-vapor interface shapes which are basically flat in a gravity dominated regime would be spherical in a zero-gravity environment, with the contact angle preserved.

In reference 8, an experimental investigation was conducted which helped verify this theoretical work for stable low gravity equilibrium interface configurations in spheroidal containers. The contact angle of the liquid-solid interface was  $0^\circ$  and tanks with eccentricities ranging from 0.80 to 0 (spherical) were tested. Although interface configurations were analyzed for several different system conditions (Bond number, tank geometry, fill level, etc.), the interface was always oriented symmetrically about the tank minor axis.

It is reasonable to deduce from the theory, that other locations of equilibrium liquid-vapor interfaces may be possible in tanks of this geometry - as long as the minimum energy requirement is satisfied. Three test conditions were varied in this study in order to examine this possibility. The first condition involved changing the initial liquid position with respect to the

tank axis. By doing this it was possible to see if the resulting quiescent zero-g interface could exist at more than one location with respect to these axes. The second condition involved varying the liquid fill level in order to determine the effect that the size of the interface, or ullage, had on the potential for other interface locations. Finally, two different fluids were used to determine the effect fluid properties might have on the tests. The only property that did not vary from one fluid to another was the  $0^\circ$  contact angle characteristic on the test container surface. The results of the drop tests indicated that varying fluid properties - specifically surface tension, viscosity and density - had no effect on the objective of determining possible liquid-vapor interface locations. For most of the initial conditions, the two fluids (ethanol and FC-43) chosen for the testing, provided a nearly quiescent zero gravity interface within 2.5 sec, thus allowing sufficient time for the observation of the final vapor bubble configuration.

### Interface Locations

A liquid that is contained in a spherical tank, under a low gravity condition, with a  $0^\circ$  contact angle, will have a stable liquid-vapor interface configuration of a complete sphere, as predicted by theory. This vapor bubble configuration satisfies both the contact angle and constant radius of curvature requirements for a stable low Bond number interface, and can exist at any location in the tank. If the container is elongated (a spheroid), the boundary of the tank walls may prohibit certain size interfaces from forming this spherical configuration at specific locations in the tank. This is particularly the case at the area of the spheroidal container where the radius of curvature of the wall is the smallest. However, if a spherical vapor bubble can be accommodated at this location of the tank, it should also be able to exist at any other location in the container.

A simple numerical analysis was performed to determine the locations where different diameter low gravity vapor bubbles could exist within the walls of the container used in the tests ( $e = 0.68$  cm,  $x = 2.0$  cm). The analysis compared the coordinates of the various size spheres with the coordinates of the spheroid, for specific sphere locations. From this analysis it was possible to determine where, in such a tank, different size low gravity vapor bubbles could, and could not, exist. Experiments were then performed in the drop facility to determine the validity of this analysis.

Initial tank orientation. - Most of the experimental drops performed in the Zero-Gravity Facility were conducted such that the tank major axis was aligned with the drop axis of the test vehicle. A few experimental tests were also performed with the spheroid container rotated clockwise so that a  $30^\circ$  angle existed between the tank major axis and the drop axis. This variation of the initial tank orientation affected both the starting position and resulting transient motion of the interface as it formed its zero-g configuration during the drop. However, the several conclusions which follow, regarding the possible equilibrium zero-gravity liquid-vapor interface positions, were unaffected by the initial tank orientation.

High liquid fill levels ( $V_0/V_t \geq 0.80$ ). - The higher the liquid fill level in the container, the smaller the low-g vapor bubble will be. For a liquid which possesses a  $0^\circ$  contact angle on the test container surface, and which occupies 80 percent of the test container volume, the resulting zero Bond



number interface will have a constant radius of curvature of 1.06 cm. From the results of the numerical analysis, a sphere of this size can exist at the area of the container where the radius of curvature of the wall is the smallest (i.e., the tank vertices), and consequently at any other location within the tank.

The initial condition of the experimental system was such that an 80 percent liquid fill level was tested with the liquid symmetrically located about the container major axis before entry into the low-gravity environment (fig. 9(a)). Once into the drop phase of the experiment, the liquid-vapor interface underwent an oscillatory motion, but remained symmetric about the tank major axis (figs. 9(b) to (d)). This transient motion of the interface created little disturbance to the bulk liquid, and was damped out after approximately 2 sec into the 5 sec test period (fig. 9(e)). Figure 10(a) shows the final observed interface configuration, and figure 10(b) is a plot of the actual interface after correcting for refraction. The plot indicates a liquid-vapor interface configuration that is nearly spherical and is approximately tangent to the wall at one of the vertices of the test container. The figure also shows that this experimental interface is slightly smaller than a sphere representing the actual size of a vapor bubble for the fill level tested. This discrepancy was evident in most of the data collected and was considered within the experimental error range due to the measurement difficulties previously discussed.

Higher liquid fill levels were also tested, and the equilibrium interface configurations behaved very similar to the 80 percent fill case (fig. 11). These results indicate that at high fill levels (80 percent and higher), the resulting low gravity equilibrium vapor bubble can exist at any position in the test container - including positions off of the tank axes as shown in figure 12. Figure 12 shows a test where the liquid was initially positioned asymmetrically and occupied 90 percent of the test container volume. The final shape is not symmetric about the tank major or minor axes, but instead has formed a spherical interface configuration at an apparently random location in the container.

Moderate liquid fill levels ( $0.46 < V_0/V_t < 0.80$ ). - Again, a series of 5 sec zero-gravity tests were carried out with the liquid initially symmetric about the tank major axis. Fill levels were varied between 80 and 46 percent. The motion of the liquid-vapor interface upon entry into the zero-gravity environment was identical to that described for the higher fill levels, except that the oscillatory motion of the interface took about 3 sec to damp out, due to the larger size of the interface.

Figure 13 shows the results of a 70 percent fill test. A plot of the expected and observed liquid-vapor interfaces can be seen in the figure. This diagram illustrates that the interface is located near the area of the container where the wall curvature is greatest (i.e., at one of the vertices) - in a position similar to that observed in the higher fill level tests. The numerical analysis demonstrated that, although a vapor bubble resulting from a 70 percent filling cannot be tangent to the tank wall at one of the vertices and still form a sphere, it can come within 0.02 cm of the wall at this area of the container while maintaining a spherical shape. Thus, the experimental and numerical results indicate moderate fill levels, as low as 70 percent, can form low Bond number interfaces that can essentially exist anywhere in the test container.

Investigating moderate fill levels below 70 percent showed that the interface has a tendency to be situated away from the vertices of the spheroidal container, and more towards the central area of the tank. For instance, the numerical analysis showed that for a 60 percent fill case, the low-gravity interface must be positioned at least 0.10 cm away from one of the container vertices before it is capable of forming a sphere within the tank boundaries. The experimental data indicates this to be the case. In figure 14, the resulting low Bond number interface configuration for a 60 percent filling test is presented. As can be seen in the figure, the final interface shape is a sphere that has been positioned near but clearly displaced from a vertex of the tank.

Low liquid fill levels ( $V_0/V_t \leq 0.46$ ). - As the liquid fill level decreases, the radius of curvature of the liquid-vapor interface increases until it reaches a size where it cannot exist as a single sphere within the tank walls. When this occurs (at a fill level of 46 percent or less for the tank tested), a spherical interface can no longer be tangent to the wall at one point or be completely encapsulated within the container boundaries. Instead, the liquid-vapor configuration meets its minimum energy requirement for a stable low gravity interface by forming a sphere that is tangent to the container boundary at two points (fig. 15), or by forming a shape which is a segment of a sphere. This consequently results in an annular interface with the liquid positioned against the tank walls. In reference 8, this interface was obtained for appropriate fill levels in tests where the liquid was symmetric about the tank minor axis prior to entry into the drop mode of the experiment. One of the test results is depicted in figure 16.

Since the liquid-vapor interface can only form a segment of a sphere, and must still satisfy the  $0^\circ$  contact angle condition, the resulting annular interface should always be symmetric about the container minor axis. That is, it appears the  $0^\circ$  contact angle and constant radius of curvature requirements cannot be met for an interface configuration of a spherical segment that is located along the sides of the tank (symmetric about the tank major axis), or in an asymmetric position in the spheroidal container.

Drop tests were performed in order to verify this idea. As before, the liquid was initially located symmetrically about the container major axis. The objective of the test was to determine if the low-gravity interface would form a configuration similar to that observed when the interface was initially symmetric about the tank minor axis (fig. 16). Figure 17 shows a series of photographs of the interface during the drop. In figure 17(a) the initial condition is pictured. After 0.20 sec into the zero-gravity environment, the interface has formed into a highly curved shape. (fig. 17(b)). The liquid-vapor interface, however, was still not stable, and did not stop moving towards the other end of the container (figs. 17(c) and (d)). Because the formation time of a stable interface was longer than the drop time, a final interface shape for this experimental set-up was impossible to determine. It is obvious, however, that the liquid-vapor interface observed was not stable. Instead, the interface appeared to be migrating to a configuration similar to that seen in figure 16. It is the opinion of the author, that if enough zero-gravity time was available for formation of a stable interface, the final configuration for this fill level would always be identical with that found in reference 8 (fig. 16).

A qualitative summary of the zero-gravity experimental results for the entire test program described is illustrated in figure 18. The plot shows that, for the tank tested, there are several conditions where the liquid-vapor

interface may or may not have more than one location in the container. Specifically, any liquid filling that is less than or equal to 46 percent will result in a zero-gravity interface configuration which can have only one location in the tank. This is represented on the plot by a horizontal line from a liquid filling of 0 to 46 percent corresponding to one on the vertical axis (number of interface locations). Starting at a fill level of 46 percent, the number of locations increases with increasing fill level and asymptotically approaches the number of locations for an 80 percent fill case. For fill levels of 80 percent or greater the interface can have an infinite number of locations in the spheroidal tank. These fill levels are represented by the shaded area of the plot.

Effect of Bond number. - It should be noted that the experiment and analysis that was carried out considered only zero-gravity or zero Bond number interface shapes. The value of the Bond number and the direction of the equivalent gravitational field with respect to the container axes, will also have an effect on where the stable interface will exist in a spheroidal container. For instance, for some higher fill levels it was found that the interface could actually exist anywhere in the tank under a very low-gravity environment. If, however, an acceleration was applied to the tank, these interfaces might exist in only specific locations in the container. Further investigation is needed to determine the value of the Bond number that can create this situation.

## SUMMARY OF RESULTS

An experimental study was conducted to determine if equilibrium liquid-vapor interfaces can exist at more than one location in an oblate spheroid under zero-gravity conditions. The investigation employed an oblate spheroidal tank with an eccentricity of 0.68 and a semimajor axis of 2.0 cm. Test liquids were restricted to those which possess near  $0^\circ$  static contact angles on the tank surface. Experiments were conducted in a low gravity environment on the order of  $10^{-5}$  g's yielding system Bond numbers that were effectively zero. The study provided the following results:

1. The tank fill level and spheroid eccentricity not only determine the low gravity interface shape (ref. 8), but they also determine where in the tank a stable equilibrium interface may be positioned.
2. For high liquid fill levels of 80 percent or greater, the corresponding low gravity spherical interface configurations can exist anywhere in an oblate spheroidal container with an eccentricity of 0.68 and major axis of 2 cm.
3. For fill levels of 46 percent or less, it appears that only centrally located liquid-vapor interface configurations can exist in the container tested.

## ACKNOWLEDGMENT

The author greatly acknowledges the support provided by NASA Lewis personnel concerning the assembly of the experimental hardware for this investigation, with particular reference to Mr. Ray Sotos.

## REFERENCES

1. Aydelott, John C.; Carney, Michael J.; Hochstein, John I. : NASA Lewis Research Center Low-Gravity Fluid Management Technology Program NASA TM-87145, 1985.
2. Petrash, Donald A.; Nussle, Ralph C.; and Otto, Edward W.: Effect of Contact Angle and Tank Geometry on the Configuration of the Liquid-Vapor Interface During Weightlessness. NASA TN-D-2075, 1963.
3. Reynolds, W.C.; Saad, M.A.; and Satterlee, H.M.: Capillary Hydrostatics and Hydrodynamics at Low g. Report LG-3, Stanford Univ., Sept. 1, 1964.
4. Satterlee, H.M.; and Reynolds, W.C.: The Dynamics of the Free Liquid Surface in Cylindrical Containers Under Strong Capillary and Weak Gravitational Conditions. Report LG-2, Standord Univ., May 1, 1964.
5. Symons, Eugene P.; and Abdalla, Kaleel L.: Liquid-Vapor Interface Configurations in Toroidal Tanks During Weightlessness. NASA TN-D-4819, 1968.
6. Hastings, Leon J.; and Rutherford, Reginald, III: Low Gravity Liquid-Vapor Interface Shapes in Axisymmetric Containers and a Computer Solution. NASA TM-X-53790, 1968.
7. Concus, P.; Crane, G.E.; and Satterlee, H.M.: Small Amplitude Lateral Sloshing in Spheroidal Containers Under Low Gravitational Conditions. (LMSC/A944673, Lockheed Missiles and Space Co; NASA Contract NAS3-9704) NASA CR-72 500, 1969.
8. Salzman, Jack A.: Low-Gravity Liquid-Vapor Interface Configurations in Spheroidal Containers. NASA TN-D-5648, 1970.
9. Coney, Thom A.; Salzman, Jack A.: Lateral Sloshing in Oblate Spheroidal Tanks Under Reduced and Normal Gravity Conditions. NASA TN-D-6250, 1971.

TABLE I. - PROPERTIES OF TEST LIQUIDS

Liquid	Surface tension, dynes/cm	Density, g/cm <sup>3</sup>	Dynamic viscosity, cP	Contact angle with acrylic plastic, degrees
Ethanol (at 20 °C)	22.3	0.79	1.20	0
F.C. - 43 (at 20.5 °C)	16.8	1.90	6.41	0

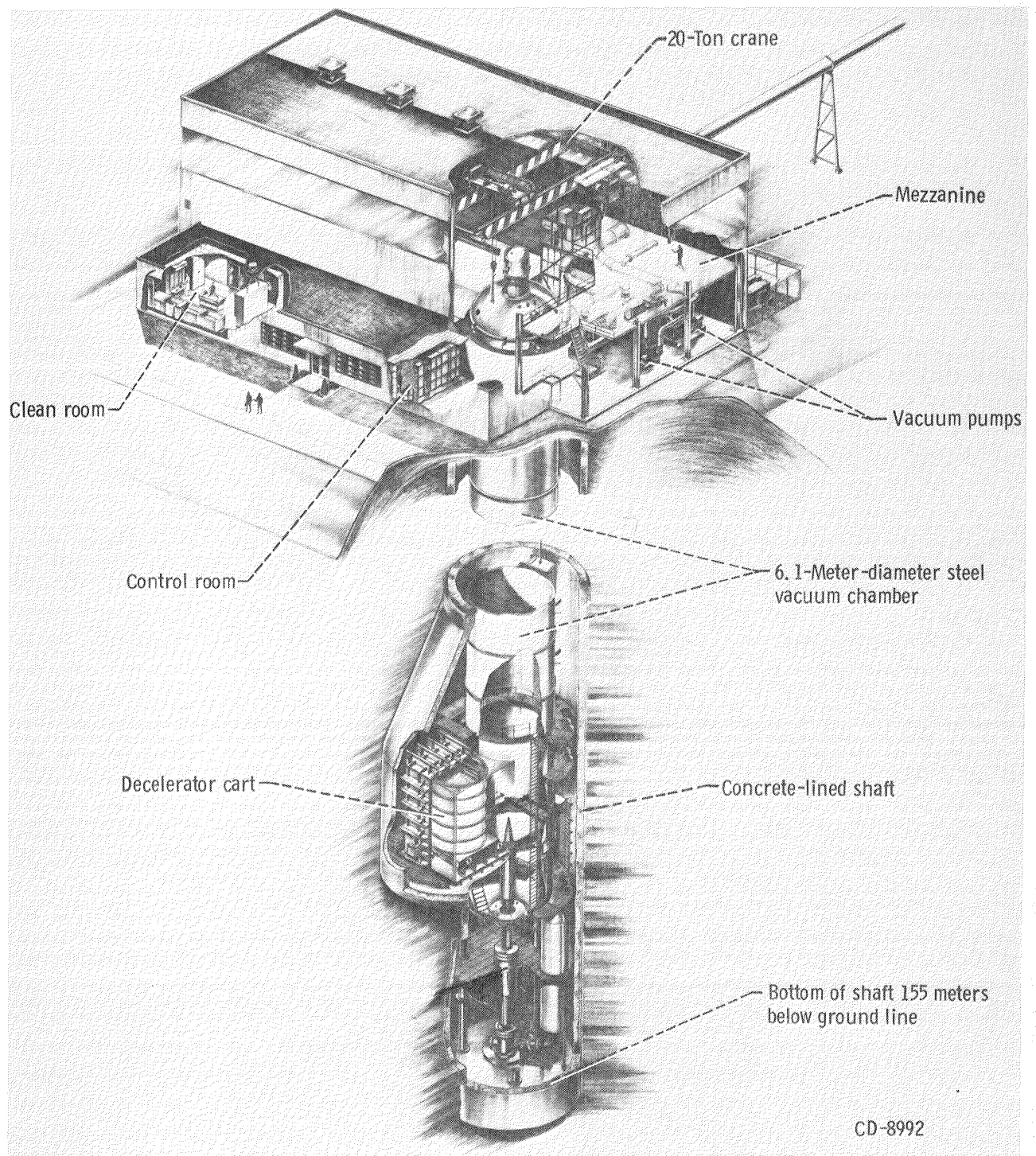
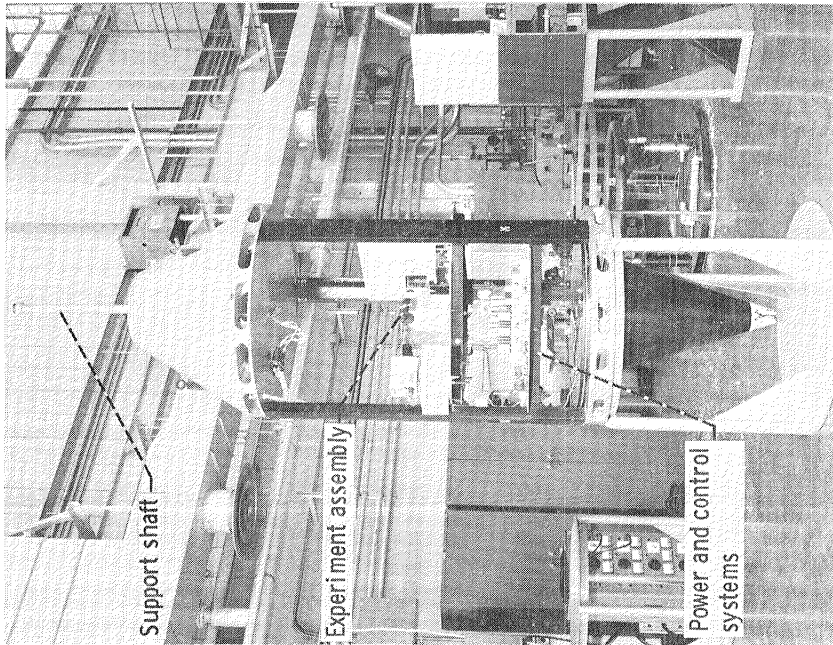
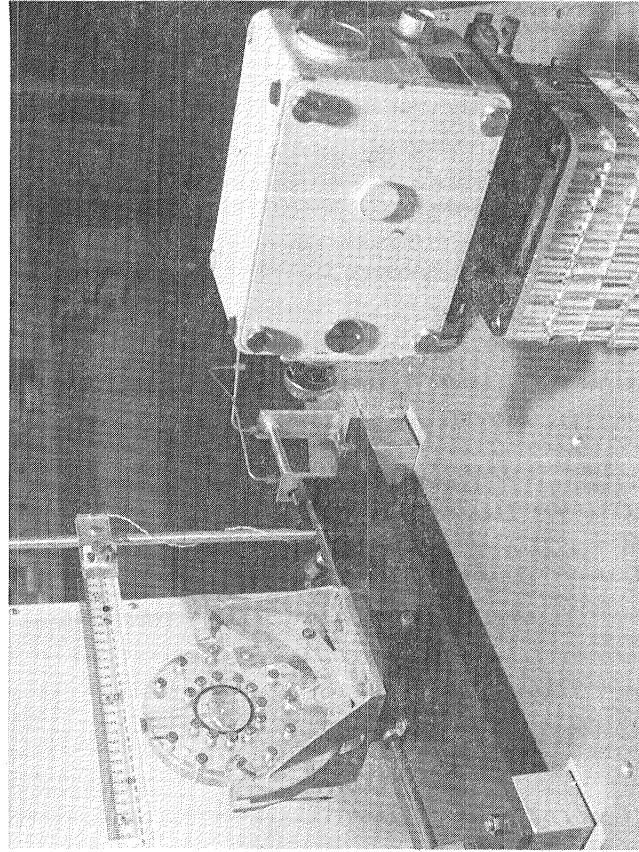


Figure 1. - Schematic view of Zero-Gravity Facility.



(a) Test vehicle.



(b) Experiment assembly.

Figure 2. - Experimental vehicle used for low-gravity tests.

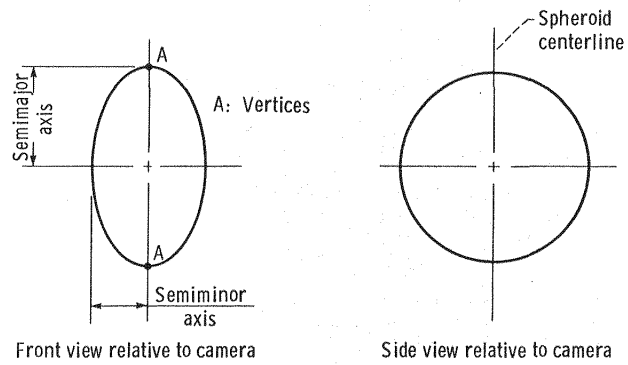


Figure 3. - Oblate spheroid tank configuration.

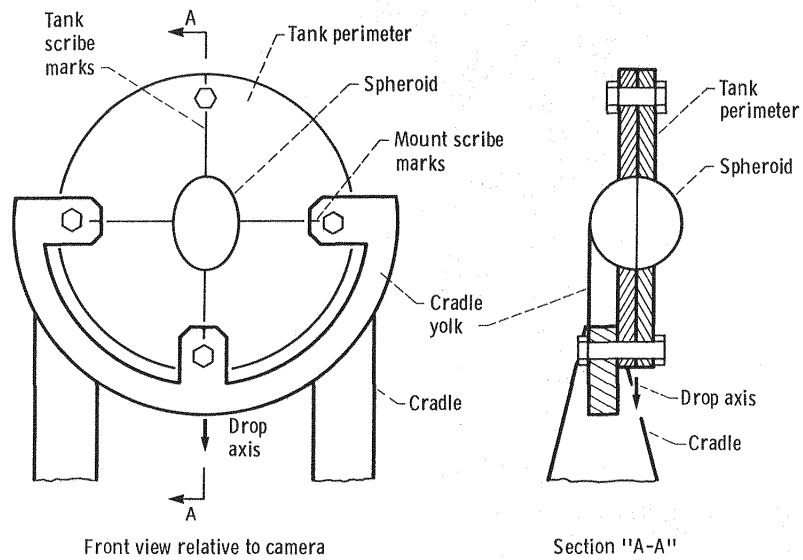


Figure 4. - Mounting configuration of the spheroidal tank on the support cradle.

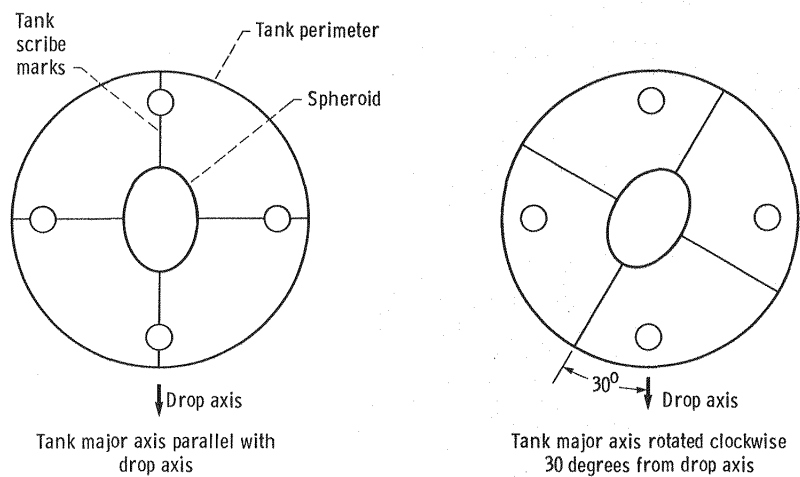


Figure 5. - Spheroidal tank orientation relative to drop axis.

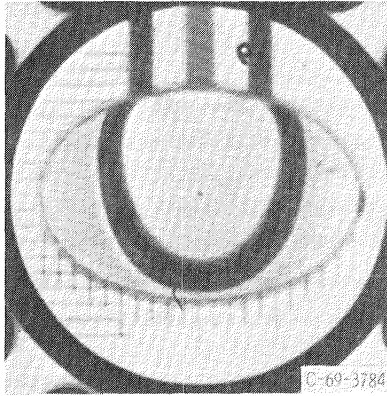


Figure 6. - Original data photograph of interface symmetric about tank minor axis. (Ref. 8)

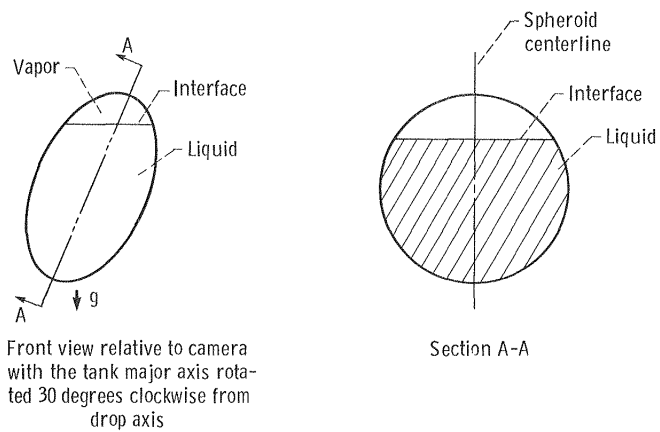
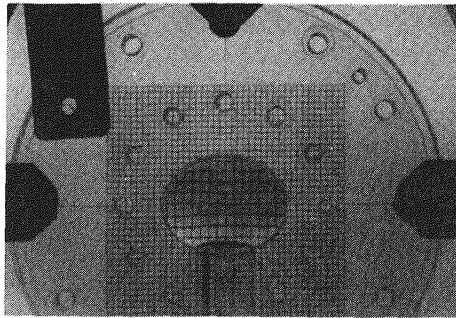


Figure 7. - Symmetry of interface about spheroid centerline prior to drop for a typical initial condition.





Refraction calibration photograph

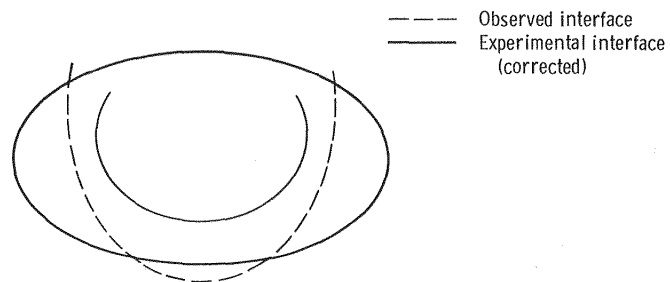
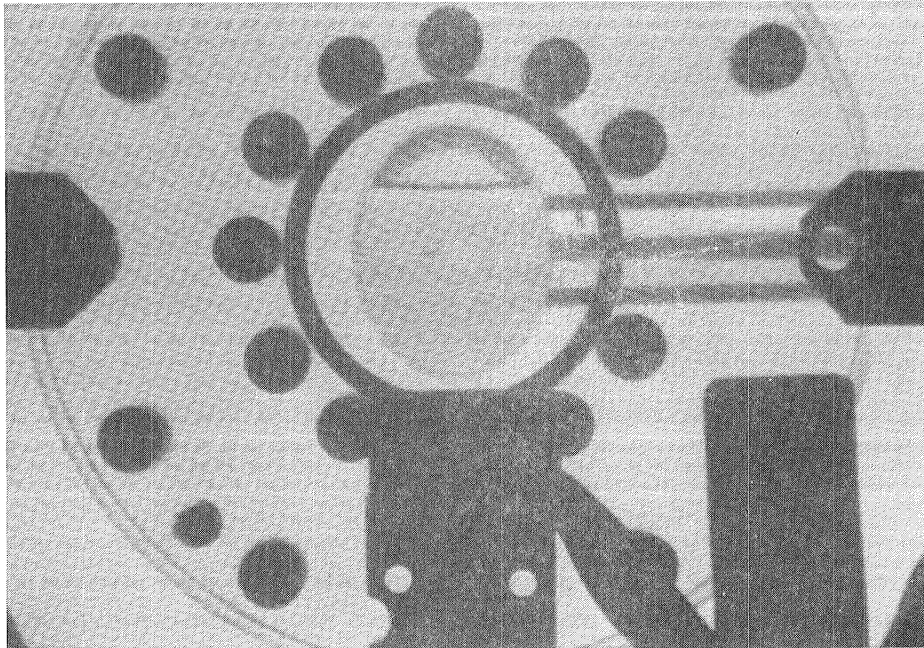
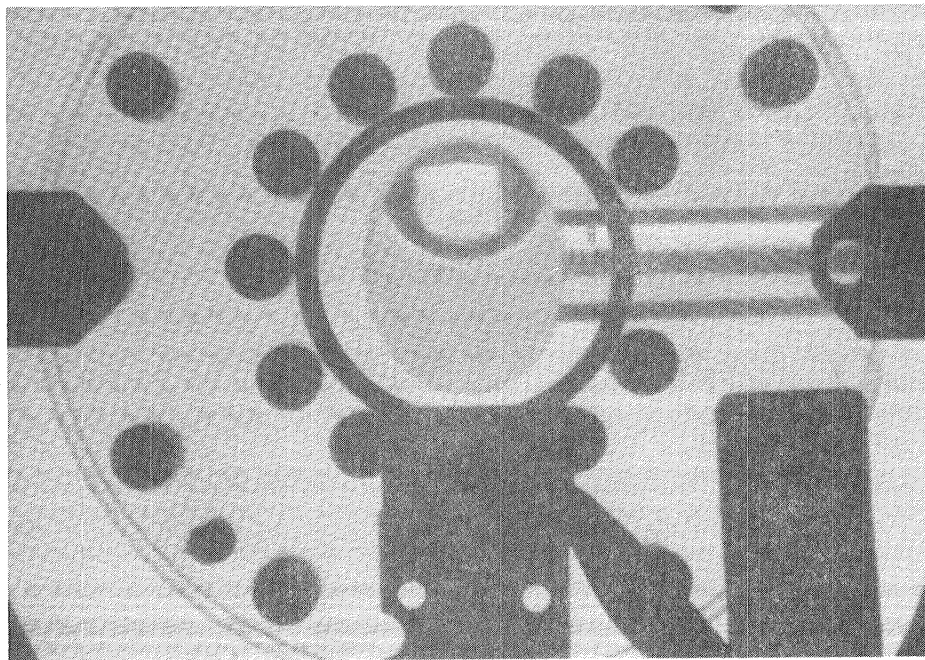


Figure 8. - Correction procedure for interface data. Interface shown illustrates interface configuration symmetric about tank minor axis.

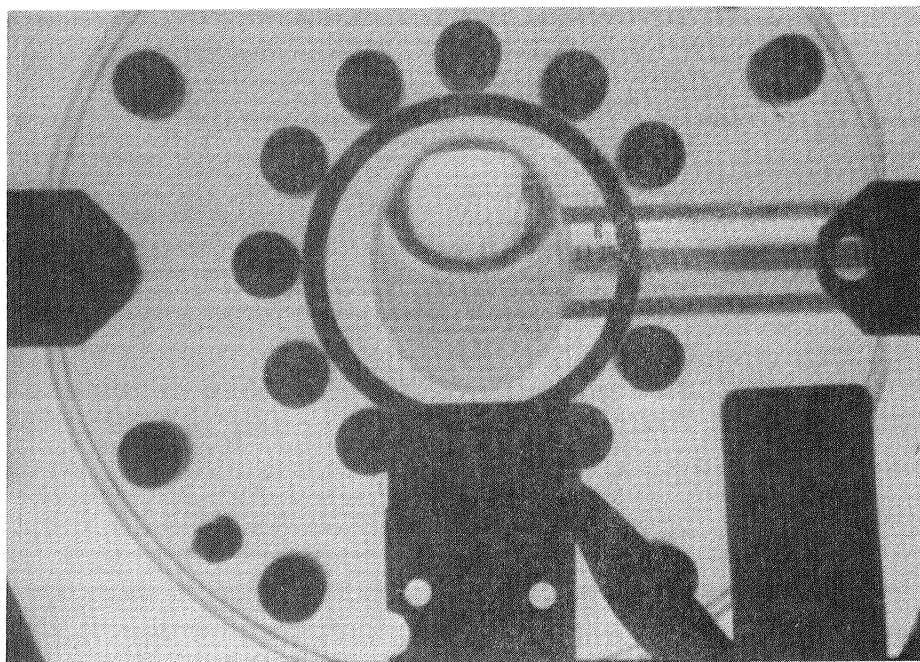


(a) High bond number configuration; time, 0 second.

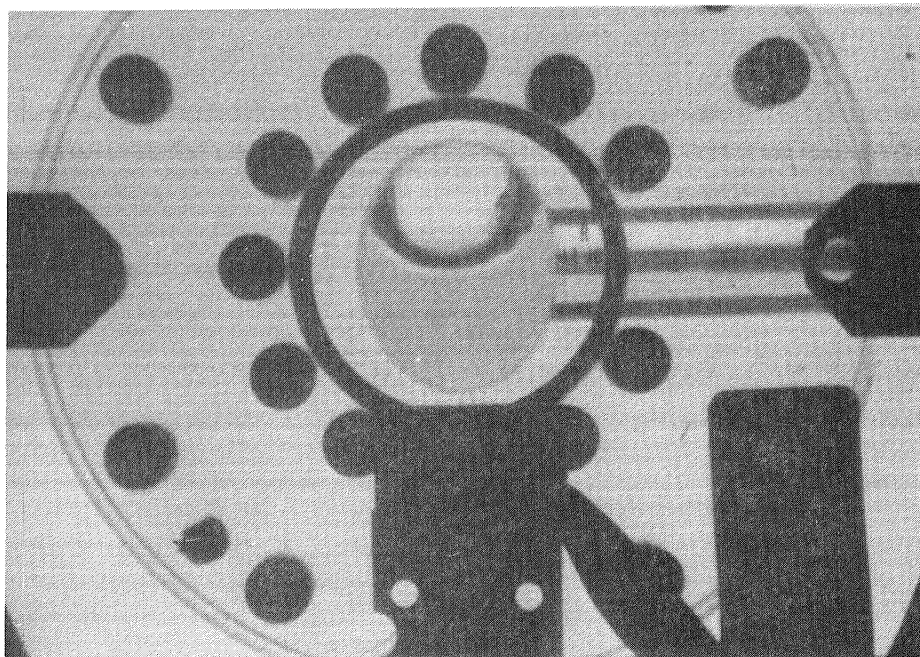


(b) Maximum interface distortion; time, 0.13 second.

Figure 9. - Transient motion of interface upon entering low gravity. 80 percent filling; interface initially symmetric about tank major axis.

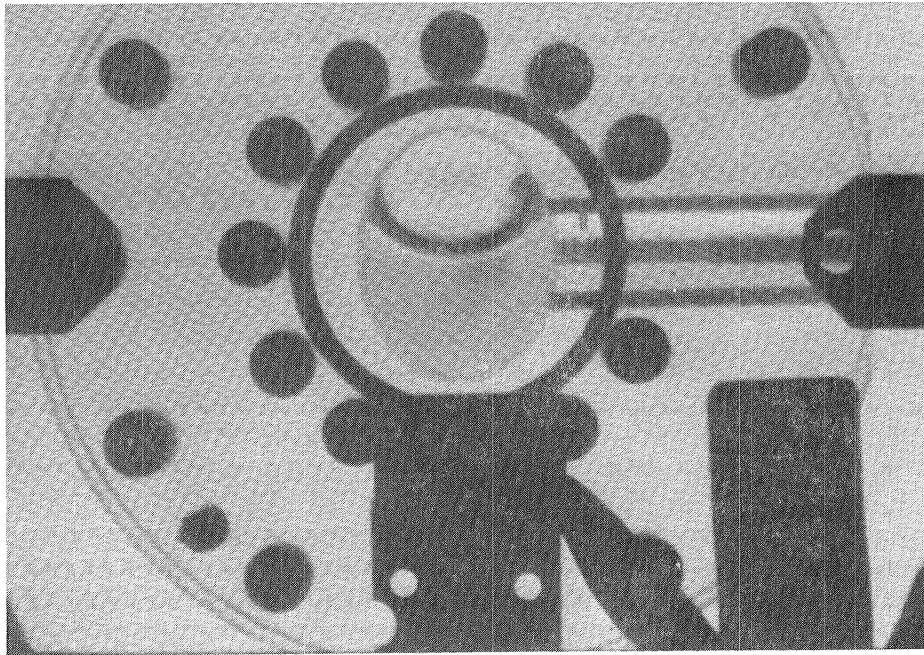


(c) Transient interface shape; time, 0.18 second.



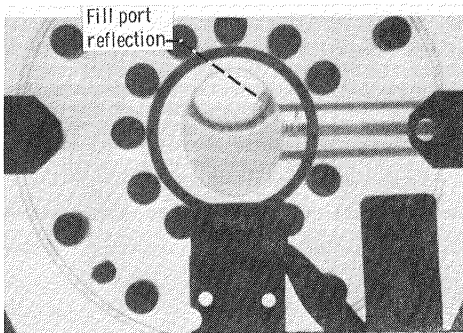
(d) Damping of liquid motion begins to take place; time, 0.53 second.

Figure 9. - Continued.

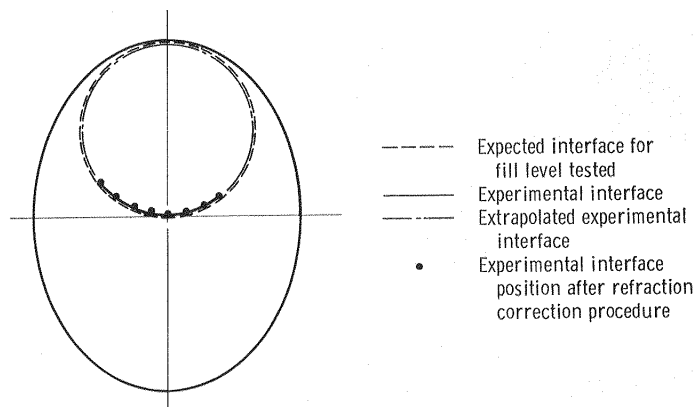


(e) Nearly quiescent interface; time, 2.20 seconds.

Figure 9. - Concluded.



(a) Final observed liquid-vapor interface configuration.



(b) Final experimental liquid-vapor interface after correcting for refraction and expected interface for the fill level tested.

Figure 10. - Final interface configuration; 80 percent filling; interface initially symmetric about tank major axis; time, 5.00 seconds.

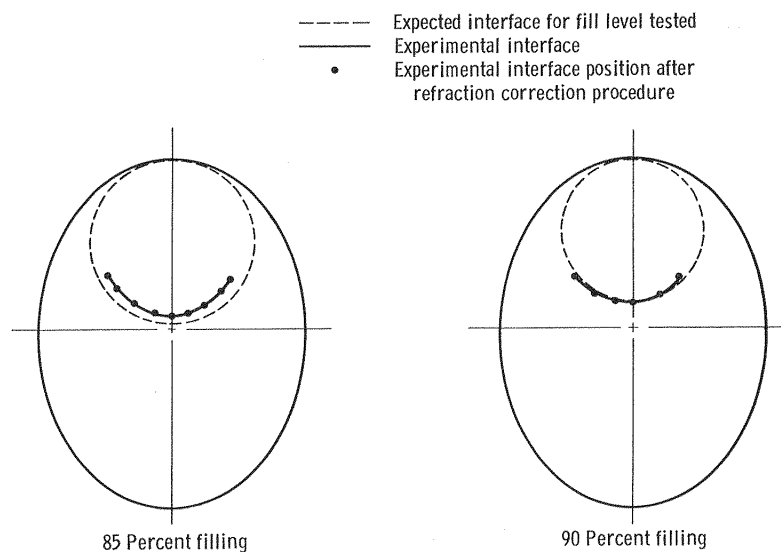
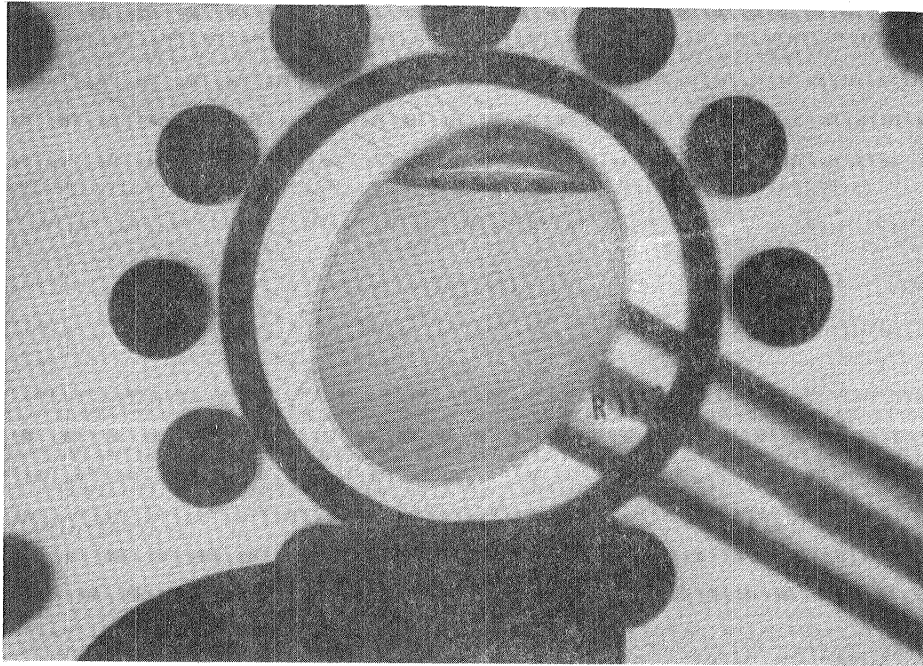
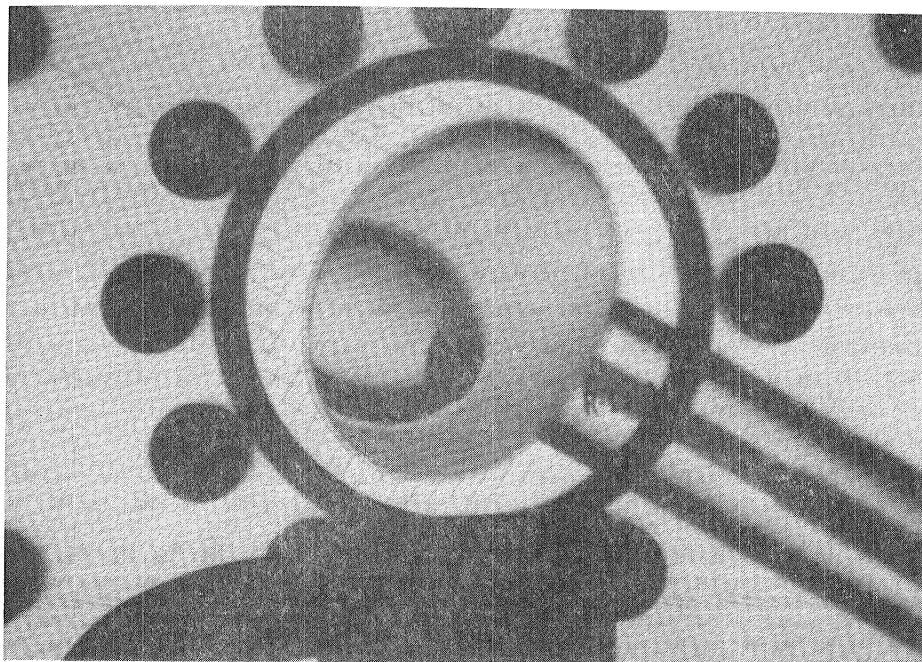


Figure 11. - Final interface configuration; interface initially symmetric about tank major axis; time, 5.00 seconds.





(a) Initial interface position; time, 0 second.



(b) Final zero-gravity interface configuration; time, 5.0 seconds.

Figure 12. - Interface configuration resulting from initially asymmetric condition. 90 % filling.

- Expected interface for fill level tested
- Experimental interface
- - - - Extrapolated experimental interface
- Experimental interface position after refraction correction procedure

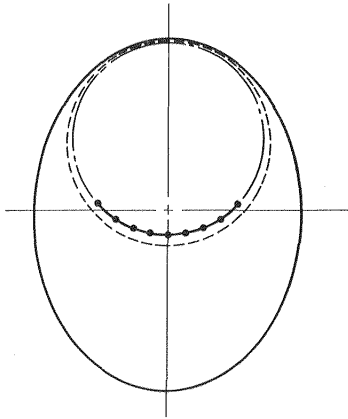


Figure 13. - Final interface configuration; 70 percent filling; interface initially symmetric about tank major axis; time, 5.05 seconds.

- Expected interface for fill level tested
- Experimental interface
- - - - Extrapolated experimental interface
- Experimental interface position after refraction correction procedure

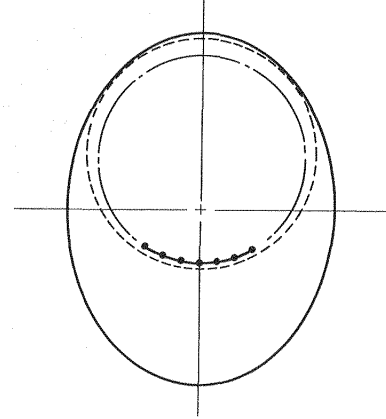


Figure 14. - Final interface configuration; 60 percent filling; interface initially symmetric about tank minor axis; time, 5.05 seconds.

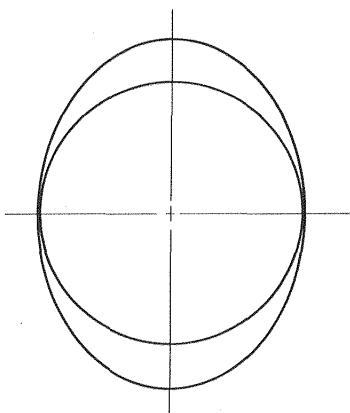


Figure 15. - Expected zero-gravity interface configuration for the experimental spheroidal tank at a 46-percent fill level. Interface is tangent to the wall boundary at two points, where the tank boundary and tank minor axis intersect.

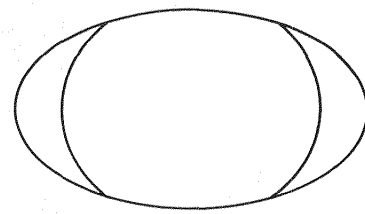
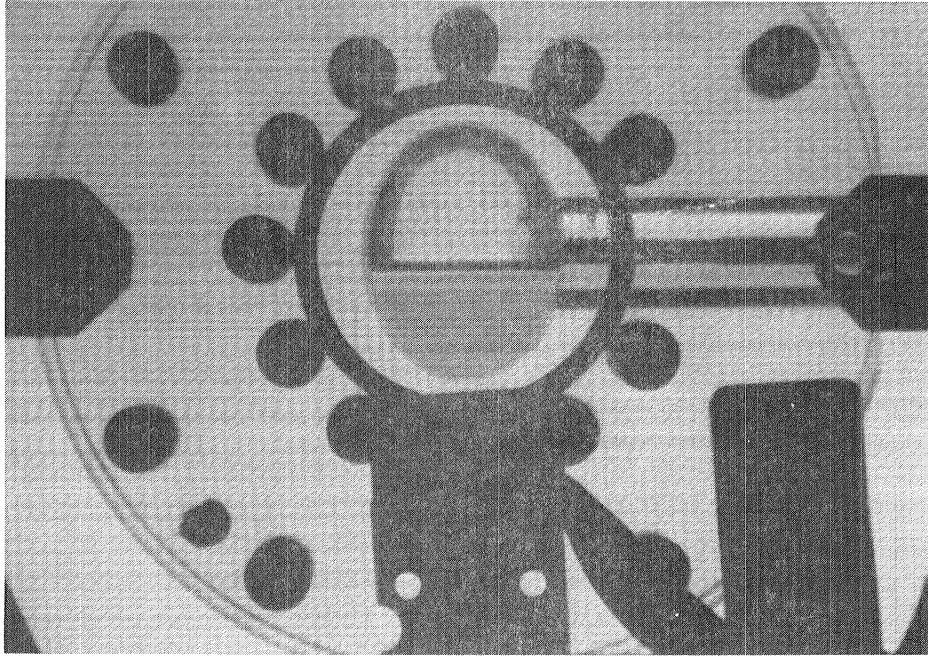
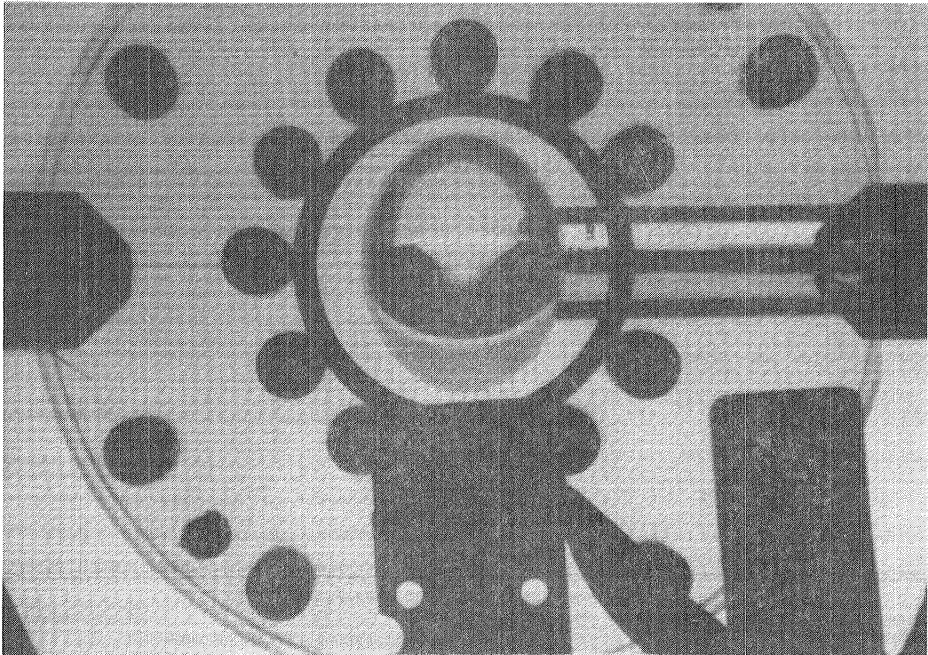


Figure 16. - Typical annular interface found in reference 8.



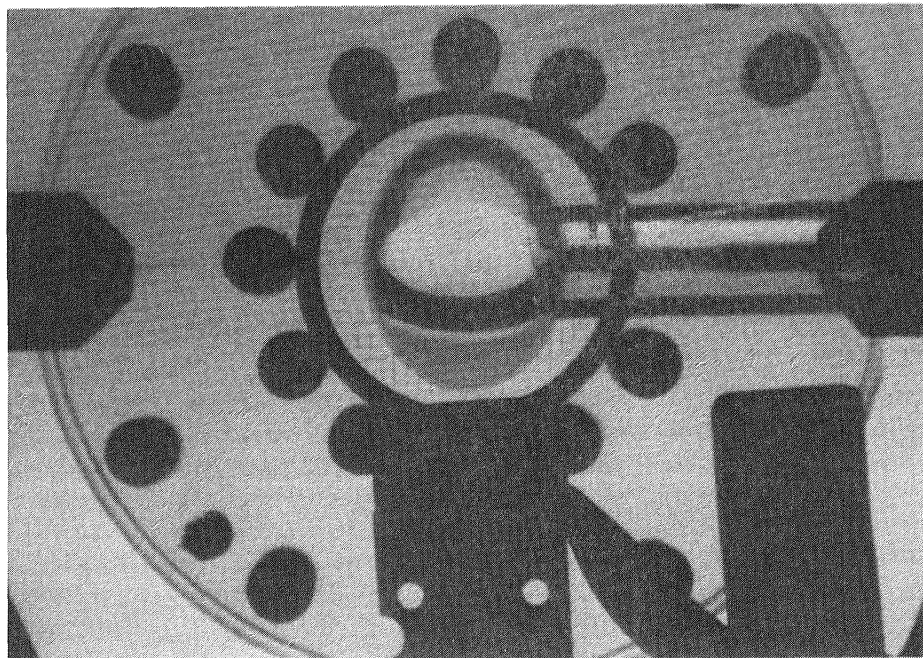
(a) High bond number configuration; time, 0 second.



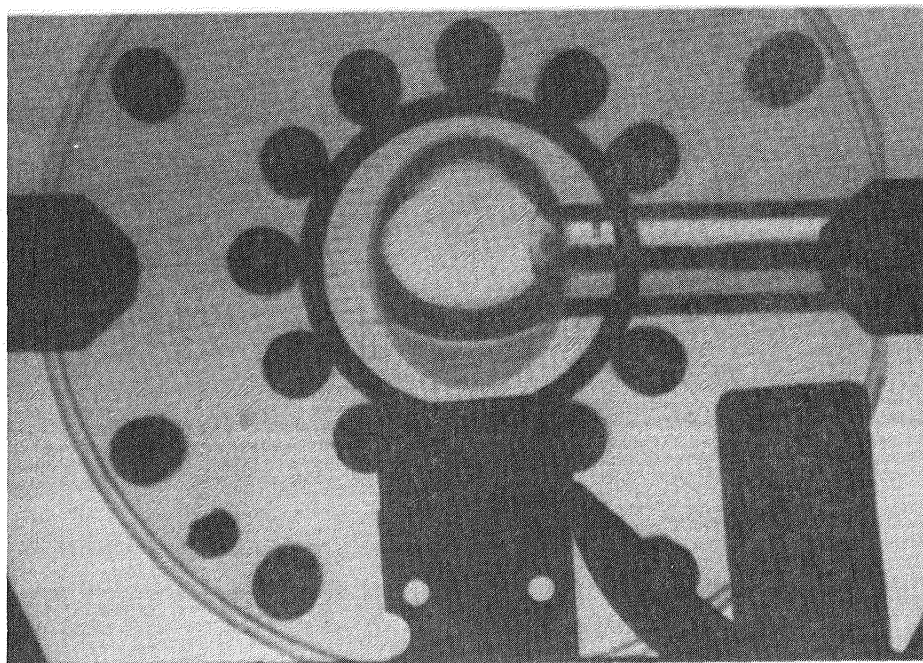
(b) Highly curved interface after entry into zero-gravity; time, 0.20 second.

Figure 17. - Interface position as a function of time into the drop period; 37.5 % filling; interface initially symmetric about tank major axis.





(c) Transient interface configuration; time 0.50 second.



(d) Transient interface configuration; time, 4.99 seconds.

Figure 17. - Concluded.

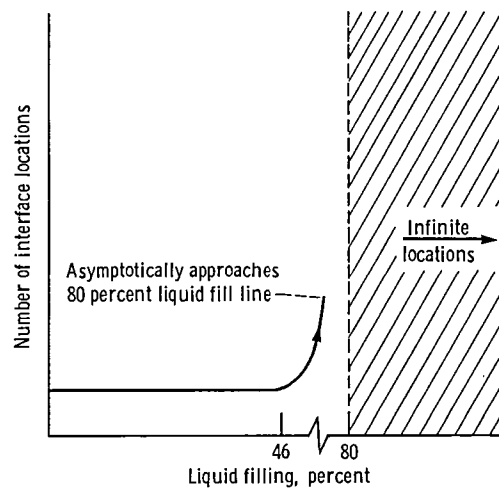


Figure 18. - Qualitative summary of interface locations as a function of fill level. Tank eccentricity, 0.68; tank semimajor axis, 2 centimeters.

1. Report No. <b>NASA TM-87147</b>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle  <b>Liquid-Vapor Interface Locations in a Spheroidal Container Under Low Gravity</b>		5. Report Date <b>April 1986</b>	
		6. Performing Organization Code <b>927-60-01</b>	
7. Author(s)  <b>Michael J. Carney</b>		8. Performing Organization Report No. <b>E-2936</b>	
		10. Work Unit No.	
9. Performing Organization Name and Address  <b>National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135</b>		11. Contract or Grant No.	
		13. Type of Report and Period Covered <b>Technical Memorandum</b>	
12. Sponsoring Agency Name and Address  <b>National Aeronautics and Space Administration Washington, D.C. 20546</b>		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract  <p>As a part of the general study of liquid behavior in low-gravity environments, an experimental investigation was conducted to determine if there are equilibrium liquid-vapor interface configurations that can exist at more than one location in oblate spheroidal containers under reduced gravity conditions. Static contact angles of the test liquids on the spheroid surface were restricted to near 0°. The experiments were conducted in a low-gravity environment (on the order of <math>1 \times 10^{-5}</math> g). An oblate spheroidal tank was tested with an eccentricity of 0.68 and a semimajor axis of 2.0 cm. Both quantitative and qualitative data were obtained on the liquid-vapor interface configuration and position inside the container. The results of these data, and their impact on previous work in this area, are discussed. Of particular interest are those equilibrium interface configurations that can exist at multiple locations in the container.</p>			
17. Key Words (Suggested by Author(s))  <b>Liquid-vapor interface; Low gravity; Oblate spheroidal container; Weightlessness</b>		18. Distribution Statement  <b>Unclassified - unlimited STAR Category 34</b>	
19. Security Classif. (of this report) <b>Unclassified</b>	20. Security Classif. (of this page) <b>Unclassified</b>	21. No. of pages	22. Price*

**End of Document**